

Yang H, Zhang BF, Li R, Zheng G, Zivkovic V.

[Particle dynamics in avalanche flow of irregular sand particles in the slumping regime of a rotating drum.](#)

*Powder Technology* 2017, 311, 439-448.

**Copyright:**

© 2017. This manuscript version is made available under the [CC-BY-NC-ND 4.0 license](#)

**DOI link to article:**

<http://dx.doi.org/10.1016/j.powtec.2017.01.064>

**Date deposited:**

25/01/2017

**Embargo release date:**

10 February 2018



This work is licensed under a

[Creative Commons Attribution-NonCommercial-NoDerivatives 4.0 International licence](#)

# Particle dynamics in avalanche flow of irregular sand particles in the slumping regime of a rotating drum

H. Yang<sup>1ab</sup>, B. F. Zhang<sup>1a\*</sup>, R. Li<sup>1a</sup>, G. Zheng<sup>1c</sup>, V. Zivkovic<sup>2\*</sup>

<sup>1</sup> a. School of Optical-Electrical and Computer Engineering, b. Shanghai Key Lab of Modern Optical System, c. School of Medical instrument and food engineering, University of Shanghai for Science and Technology, Shanghai, 200093, China

<sup>2</sup> School of Chemical Engineering and Advanced Materials, Newcastle University, NE1 7RU, United Kingdom

(Received 14 Aug 2016)

Corresponding author: Vladimir.Zivkovic@newcastle.ac.uk; zgdin@163.com

**Abstract:** Slowly rotating drums are important due to their industrial application, but also as a simple model system for studying transient avalanche processes. A speckle visibility spectroscopy (SVS) alongside a simple imaging technique was used to measure the time-resolved avalanching of 1.3 mm diameter sand particles in a 35% full rotating drum operating in the slumping regime. The major difference from spherical particle dynamics is visual observation of granular compaction in the upper part of the drum at the beginning of the avalanching process which is not present in experiments with spherical particles. The SVS measurement of avalanching shows that the fluctuation velocity, so called granular temperature, increased sharply before plateauing then decreases sharply to zero during a typical avalanche event which is different to spherical particle behavior where these transitions are more gradual. Furthermore, the granular dynamics of avalanching flow is influenced by a visually observed flowing mound down the avalanching surface so there are more characteristics peaks in plateau region of the signal for measurement point in the lower part of the bed. Overall, the observed plastic deformation is influencing the dynamics of the system in several ways indicating the importance of considering particle shape in the study of granular flow dynamics.

## I. INTRODUCTION

Granular materials in rotating drums are of wide interest not only because of their extensive use in the chemical, minerals, ceramic, pharmaceutical and food processing contexts, but also as model systems in the study of natural disasters, such as avalanches or landslides [1, 2]. The overwhelming majority of experimental and numerical studies have focused on spherical particles although granular systems in industry or nature frequently consist of non-spherical and/or irregular particles. The particle shape has a significant influence on granular dynamics [3-9] and one cannot simply extend theoretical and numerical models developed on assumption of spherical particles to these cases [10, 11]. For example, this has driven a strong effort in last couple of years in development of non-spherical discrete element method (DEM) simulations and its application to systems of academic and/or industrial interest as reviewed by Lu *et al.* [12] and Zhong *et al.* [13]. Still, there is little knowledge about the granular dynamics of non-spherical particles and irregular particles inside rotating drum.

Experimental investigations of non-spherical and irregular particle behavior in rotating drums are scarce and rather limited in scope. The majority of studies were about mixing starting from the sixties [14, 15] with several studies in the following decades [3-9]. These studies used various particles like rice [3, 15], oat [15], sand [4, 14], shale [7], limestone [4, 5] and tablets [8, 9] with some observations that mixing is probably promoted by sphericity [8, 9, 15]. Henein *et al.* [16] determined that transition to rolling regime for irregular particles is at higher rotating speeds and corresponding Froude number in comparison with spherical particles. Furthermore, the dynamic angle of repose was higher for irregular particles [16] which was confirmed as well in more recent experiments [8, 9]. Studies on particle dynamics were even more infrequent and mostly limited to surface velocity profiles due to limitation of experimental techniques [16]. Boateng and Barr [17] determined noteworthy differences in near wall cross-section velocity profiles for irregular rice and limestone particles in comparison with spherical polyethylene particles. Longo and Lamberti [18] measured as well near wall cross-section velocity profiles using glass and sand particles but without specific discussion on the particle shape influence on the granular dynamics. Experiments with tablets [8, 19] measured higher velocity of tablets in the avalanching free-surface layer of the drum in comparison with spherical counterparts. Dube *et al.* [9] used radioactive particle tracking technique with different tablets to find that particles with an aspect ratio greater than two have significant deviation in velocity profiles and residence time in comparison with spherical particle based models. Yamane *et al.* [20] used magnetic resonance

imaging to examine the granular dynamics of irregular mustard seeds observing non-zero particulate diffusion in the bulk of the drum indicating that the so-called passive region is not completely static. There are only few experimental studies of temporal evolution of particle dynamics of transient flowing layer during discrete avalanches of slumping regime for spherical [21, 22], but none, as yet, for non-spherical particles.

Although many experimental methods are available for the study of particle dynamics in rotating drums, including particle image velocimetry (PIV) [23-25], particle tracking velocimetry (PTV) [19, 26], PEPT [27, 28], laser Doppler velocimetry (LDV) [18] and magnetic resonance imaging [20, 29], some of these are restricted to two components of motion (PIV and PTV) whilst the remainder can only resolve the granular dynamics to a fine scale with relatively poor temporal resolution or *vice versa*. In contrast, speckle visibility spectroscopy (SVS) [22, 30-32] is able to resolve the average of the three components of motion of grains in dense systems with spatiotemporal resolutions that allow the probing of the microdynamics of avalanches. We have previously used it for study of granular dynamics of both active avalanching layer [22, 33] and the passive parts in the bulk of the rotating drum [32, 33] using glass spherical particles [22, 33] and cohesive lactose powders [32].

In this paper, we report a study of the avalanching of sand particles in a rotating drum under the slumping regime by a synchronized measurement method with two SVS systems as well as an imaging technique for dynamic angle of repose measurement. After a section on the experimental setup and methods, we first report in the results section the visual observation of the avalanching of the irregular particles by imaging technique. The main part of results section is derived from analysis of synchronized SVS measurements including presentation and discussion on various statistics such as the avalanche duration, rest time, and peak fluctuation velocity. The variation of avalanche statistics with the axial and longitudinal position and drum speed are presented and analysed.

## II. EXPERIMENTAL METHOD

### A. Drum system

The results reported here were obtained in a cylindrical drum, Fig. 1, whose inner diameter,  $D$ , and length,  $L$ , are 142 mm and 200 mm respectively. The rotating drum, which is made of clear Plexiglas to permit optical access, was filled with granular material to fill 35% of its volume. The drum was placed on a pair of rollers turned by a DC motor at 0.1-2.3 revolutions per minute (RPM). Four points of the granular bed were studied here at the surface of the bed where avalanche flow occurs, two at the top (A & C points) and two in the bottom part of the bed (B & D points) as shown in Fig. 1. In order to enable study of the wall effect, one pair of points was along the axial line in the middle of the drum length (C & D points) while another was along an axial line closer to the walls (A & B points). Measurement points pair A & B and pair C & D were studied simultaneously using the SVS technique. The experimental procedure simply consists of adjusting the rotating speed of the drum by changing the voltage of the DC motor. The measurements by the imaging technique and the double SVS were taken 10 min after changing the rotating speed to avoid any instabilities.

Fig. 1 (colour online) The annotated photo of the experimental setup.. The points A ( $x = 30$  mm,  $y = 45$  mm), B ( $x = 30$  mm,  $y = -45$  mm), C ( $x = 100$  mm,  $y = 45$  mm, not shown), D ( $x = 100$  mm,  $y = -45$  mm, not shown) were the focus of the SVS analysis reported here.

### B. Granular materials

The granular materials used in this study were sieved dry glass sands between sieves of 1.0 and 1.5 mm giving median particle diameter of  $d_{p,50}^{sieve} = 1.25$  mm. We used the simple image-analysis based method of Altuhavi *et al.* [34] to characterize particle size and shape of 350 samples as follows. The stereomicroscope (Olympus, T60) was used to image sand particles as shown in Figure 2(a) using an objective magnification of 86 (pixel size: 1.585  $\mu$ m). The analysis of the captured images was performed using the MATLAB image analysis toolbox to determine several particle size and shape descriptors as shown in Figure 2(b). Debatably the best measure of the overall particle size is the equivalent projected area diameter ( $d^{EQPC}$ ) which is the diameter of a circle with equivalent projected area as a particle, an example is given in Figure 2(b) [34]. Furthermore, a Feret diameter is determined

as the distance between two tangents on opposite sides of a randomly oriented particle. The mean Feret diameter ( $d^{Fmean}$ ) is simply the average value of the minimum ( $d^{Fmin}$ ) and maximum ( $d^{Fmax}$ ) Feret diameters for each particle as shown in Figure 2(b). The Feret diameters are used to obtain the aspect ratio ( $AR$ ) as simple ratio of maximum and minimum diameter for the particle. Referring to Figure 2(b), convexity ( $C_x$ ) is the ratio between the sand grain projected area,  $A$ , and the area of the convex hull,  $B$ . Finally, the sphericity is calculated by the formula

$$S^{QP} = 2\sqrt{\pi A}/P \quad (1)$$

where  $A$  and  $P$  are the projected area and perimeter of the particle respectively [34].

Table 1 gives the average value and standard deviation for determined size and shape descriptors from a cumulative distribution by number of particles. The average diameters are 1.30 mm and 1.32 mm for the equivalent projected area diameter and Feret diameter respectively, which is very close to the median sieve diameter of 1.25 mm. Based on the determined shape descriptors shown in Table 1, the sand particles would be categorised as subangular particles in the qualitative shape measure classification [34].

Fig. 2 (colour online) (a) Example photo of glass sands particles under microscope with 1 mm scale bar and (b) corresponding binary image showing particle size and shape descriptors: equivalent projected area diameter ( $D^{EQPC}$ , red online), Feret diameters ( $D^{Fmean}$ , blue online) and convex hull.

Table 1. The averages and standard deviations of particle descriptors,  $d^{EQPC}$ ,  $\langle d^{Fmean} \rangle$ ,  $AR$ ,  $S^{QP}$  and  $C_x$ , from the cumulative distribution by numbers.

### C. Measurements by imaging techniques

In the slumping regime, intermittent flow lead to a different angle before and after each avalanche occurred, called the upper,  $\theta_U$ , and lower angle of repose,  $\theta_L$ , respectively, as shown schematically in figure 3(a). Figure 3 (b) shows the profile images of the granular materials in the drum recorded by a CCD camera (1024×1024 pixels at 50 frames/s). A weight was hung alongside the drum as a plumb line so as to facilitate evaluation of the angle of repose. The upper and lower angles of repose were measured directly from snapshots just before and after an avalanche, respectively. This was done by fitting a straight line to the surface of the granular bed and measuring the angle with the plumb line. Average angles of repose and standard deviations were derived from measurements over at least ten successive slumping cycles. In addition, the SVS measurement can be used to determine the difference between upper and lower angles of repose,  $\Delta\theta = \theta_U - \theta_L$ , by using, the relationship [22]

$$\Delta\theta = 180\omega t_r/\pi \quad (2)$$

where  $\omega$  is the angular speed of the drum in rad/s and  $t_r$  is the rest time between two successive avalanches.

The trajectory of the tracer, the particle seen as a bright spot from reflection of the light in Fig. 3 (b), is recorded by following the motion of the tracer particle. Fig. 3(c) shows an example of the trajectory of movement of the tracer without any relative movement during the elevation of the granular bed. The area of profile of the granular materials is measured by counting the number of pixels in the effective area (*i.e.* the white part) of the image after a binarization process, as shown in Fig. 3(d). The relative drum area,  $f(s)$ , is introduced as

$$f(s) = s_g/s_d \quad (3)$$

where  $s_g$  is the profile area of the granular materials and  $s_d$  is the profile area of the drum.

Fig. 3 Schematic of (a) the upper,  $\theta_U$ , and lower,  $\theta_L$ , angle of repose (b) measurement of angle of repose from the profile image of the granular materials in the drum at 1.53 RPM. (c) The trajectory of the tracer in (b) from 60 continuous images; (d) the binarized image of (b).

### D. Synchronized double SVS details

The synchronized double speckle visibility spectroscopy involves illuminating the avalanching free surface spots of the granular materials with two monochromatic DPSS lasers of wavelength  $\lambda=671$  and 532 nm respectively, Fig. 1. As a set of the SVS system, the light beams were passed through a concave lens before normally illuminating a spots of around 12 mm diameter on the inclined free surface of the granular material. The photons that emerged from the granular material after diffusing within it form a speckle pattern that was

detected using 8-bit line scan CCD cameras of  $2 \times 1024$  pixels of  $14$  by  $14 \mu\text{m}$  in size and a  $50 \text{ kHz}$  frame rate, thus, providing an exposure time of  $T = 18.5 \mu\text{s}$ . The cameras were placed with their optical axis normal to the drum and  $400 \text{ mm}$  from it, such that the ratio of pixel to speckle size was about  $0.5$ . In the absence of any motion of the particles, the scattered light is characterised by a constant intensity as illustrated by the example in Fig. 4(a). Collective motion of particles as a rigid body leads to the spatial and temporal fluctuations of the scattered light resulting in random intensity of lights across the pixels, as illustrated by the example in Fig. 4(b). However, only the relative motion of particles between each other results in blurring of the captured images and for a given exposure time, the faster the dynamics of the grains, the more the speckle image is blurred and the lower the contrast – this enables the capture of rapid changes in the granular material with time such as that which occurs in an avalanche as illustrated in the example of Fig. 4(c). This variation in intensity can be quantified by the variance of the intensity [30]

$$V_2(T) \propto \langle I^2 \rangle_T - \langle I \rangle^2 \quad (4)$$

where  $\langle \dots \rangle$  denotes the average over pixels exposed for a duration  $T$ . The proportionality constant of  $V_2(T)$  is set by the laser intensity and the ratio of speckle to pixel size (*i.e.* it is set-up dependent). It can, however, be eliminated by considering the variance ratio  $V_2(2T)/V_2(T)$  [30]. For diffusely backscattered light from particles moving with a random ballistic motion, where the power spectrum is Lorentzian [35, 36], the theory of SVS [30] gives the variance ratio as

$$\frac{V_2(2T)}{V_2(T)} = \frac{e^{-4\Gamma T} - 1 + 4\Gamma T}{4(e^{-2\Gamma T} - 1 + 2\Gamma T)} \approx \frac{1 + \frac{8}{15}\Gamma T + \frac{11}{45}(\Gamma T)^2}{1 + 1.2\Gamma T + \frac{22}{45}(\Gamma T)^2} \quad (5)$$

where

$$\Gamma = 4\pi\delta v/\lambda \quad (6)$$

The third part of Eq. (5) is a rational approximation and  $\Gamma$  can be obtained by solution of a resulting quadratic equation derived through simple manipulation. The mean fluctuation in the speed of the particles,  $\langle \delta v^2 \rangle$ , which is equal to the collision velocity and directly related to the so-called granular temperature [36], can be obtained from  $\Gamma$ , as illustrated in Fig. 4(d) which was obtained from the raw data shown in Fig 4(c). Comparison of these two subfigures clearly shows that only the relative motion of particles during avalanching is detected while the rigid body motion before and after an avalanching event is shown with the near zero collisional velocity. This, alongside the high frequency measurement, makes the approach ideal for probing in detail avalanche-related phenomena in rotating drums. Finally, the result is filtered by a Butterworth low pass filter to reduce the noise from the reflection of some particle surfaces that was not an issue in spherical glass particle experiments. Rarely, the very strong reflection of light from sand flat surfaces lead to bright vertical lines in the raw image as shown in Fig. 4(c) and subsequent breakdown of diffusely light intensity profile causing irrational collisional velocities. These points were removed from the results and replaced with the average of the five neighbours.

In order to perform the synchronized SVS measurements, two cameras were interfaced to a personal computer equipped with two PCIE-GigE cards (Intel EXPI9301CTBLK). Programming was carried out using LABVIEW. The key point of this arrangement was the elimination of the time difference between the two cameras. This was achieved by placing the cameras together and focusing them onto the same measurement area. The time difference obtained from the cross-correlation function of the two SVS signals was adjusted to be zero so the setup was perfectly synchronized.

Fig. 4 (colour online) Example of SVS raw and process data from point B of the drum: (a) intensity across the CCD pixels vs. time when the drum is stationary; (b) intensity across the CCD pixels vs. time when the drum is rotating at a speed of  $1.53 \text{ RPM}$  and no avalanche event occurs; (c) the same as (b) except an avalanche event has occurred in the period of around  $0.5\text{-}1.5 \text{ s}$ ; (d) The grey (red online) line represents the raw particle fluctuation velocity  $\langle \delta v^2 \rangle$  obtained from the data in (c), whilst the black line represents the data after being subject to a Butterworth low pass filter to reduce the noise.

### III. RESULTS AND DISCUSSION

#### A. Visual observation

Fig. 5(a) shows typical images of the granular materials during the avalanching, where the first image regarding to the beginning of the avalanche and the last one to the end of the avalanche. Analysing more than 100 successive avalanches, we got the average and standard deviation of the upper and lower angle of repose of the glass sands with  $\theta_U = 36.3^\circ \pm 1.2^\circ$ ,  $\theta_L = 30.9^\circ \pm 1.2^\circ$  at a drum speed of 1.53 RPM, which is higher than those (*i.e.*  $\theta_U = 24.8^\circ \pm 0.5^\circ$  and  $\theta_L = 23.6^\circ \pm 0.5^\circ$ ) of the spherical glass beads of similar size of 0.5-0.6 mm [22] in line with the previous experimental studies [8, 9, 16, 37] and DEM simulations (*i.e.*  $\theta_U \approx 36.3^\circ$  and  $\theta_L \approx 32^\circ$ ) [38]. This is due to increased particle interlocking because of higher particle angularity [38].

Looking at the second image, we can observe that the grains at the top of the inclined surface, near measuring point A shown in Fig. 1, begin to avalanche while those at the bottom of the surface, measuring point B in Fig. 1, still remain almost static at the beginning of the avalanching. This phenomenon is similar to that of the spherical glass beads, in that the avalanche starts at the top of the surface of the granular materials [32, 39]. As time goes on, more grains avalanche from the top of the surface and a small mound forms nearly at the centre of the surface after 0.48 s due to the fact that the avalanche front speed is slower than the surface mean particle speed for the irregular particles [37] which is different from that of the spherical particle [39-42]. With the mound avalanching to the bottom of the surface, the sand grains are stopped by the wall of the drum, collide with each other, and a mound at the bottom of the bed forms again (4<sup>th</sup> image in the series, approximately beginning of third quarter of avalanching time). Finally as the follow-up avalanches gains to the bottom of the surface, the avalanching surface recover the line profile again as shown in the last image in the series.

Fig. 5(b) shows the trajectories of the two tracers, P and Q in Fig. 5(a), which are normalized into 0 - 100 pixels for comparison. The trajectory of P is almost linear which indicate that there are no visible relative movements of the particles in the bottom part of the granular bed, while the Q tracer trajectory drops downwards quickly at the beginning of the avalanching before it reaches to the surface of the bed and submerges in the granular flow. Figure 5(c) shows the relative drum area,  $f(s)$ , during avalanching shown in figure 5(a), which decreases for a short period of time at the beginning of the avalanching and increases considerable after that. This decrease in the relative area corresponds in time with observed tracer particle drop indicating that the particles collapse suddenly at the beginning and then inflate after that during the avalanching, which is different to the avalanche dynamic of the smooth spherical glass beads (e.g. no compaction at the beginning of avalanche). Finally, Fig.5 (d) shows the time resolved change of the angle of repose measured from the whole flowing surface and from the upper half part of the surface, indicating that the angle of repose measured from the upper half part declines faster than that from the whole flowing surface for the granular compaction. Granular compaction is related to particle shape [43] and like in our experiments Zimmer *et al.* [44] only observed compaction for irregular particles in the rotating drum, although operated in a rolling regime in their case.

Fig. 5 (a) Photographs of the granular materials during avalanching from the front face at a drum speed of 1.53 RPM. (b) the trajectories of the tracers P and Q indicated in (a). (c) Time resolved change of the relative drum area,  $f(s)$ , during avalanche shown in (a). (d) Time resolved change of the angle of repose measured from the whole flowing surface (open circle) and from the upper half part of the surface (cross, the dash line in Fig. 5(a)).

#### B. Avalanching statistics

Fig. 6 shows a typical example of the synchronized particle fluctuation velocity,  $\delta v^2$ , over five slumping cycles at a drum speed of 1.53 RPM from the top, point A, and bottom, point B, of the inclined surface near the side wall. The slumping duration,  $t_d$ , rest time,  $t_r$ , lag time between point A and B,  $t_l$ , and the peak of the particle velocity fluctuation,  $\delta v_p^2$ , can be straightforwardly measured from the filtered trace for many slumping cycles as indicated in the Figure 6. Looking at a single avalanche event for the point A shows that the particle fluctuation velocity

accelerated quickly then reaching plateau for some time before decelerating quickly again in contrast to the spherical glass particle experiments where this is more progressively transition [22, 33]. The most probably reason for the difference is that the plastic deformation of observed granular compaction as another energy dissipation mechanism not present in case of smooth glass beads. The simplistic explanation would be that a change in a local angle of repose occurs, which drops considerably during compaction, but then is slowly recovering to reach the overall avalanche angle of repose, as shown in Fig. 4. However, this would imply that the granular temperature should be slowly increasing after that initial drop for point A rather than plateauing so the densification of the upper part of the bed is also influencing the granular temperature profile. Interestingly there is another increase in the granular temperature and peak right before the end of the avalanche for which we do not have explanation at the moment. Overall, this strongly suggest that for irregular particles both flow regimes and plastic deformations control the dynamics of the system similar to 2D rotating drum system experiments albeit with more regular particles [45]. Further studies using particles of different shape and surface roughness are needed to elucidate the interplay between these two phenomena further.

Fig. 6 (Color online) Synchronized particle fluctuation velocity,  $\delta v^2$ , of points A and B over five slumping cycles for a drum rotating at a speed of 1.53 RPM.

For the bottom of the avalanching surface, point B, the particle fluctuation velocity rises a little later than that of the point A, which is also in line with the visual observation and our previous paper for spherical glass beads [33]. Afterwards the signal accelerates dramatically and forms a peak before dipping to zero values, which is in line with the result that the moving mound speeds up to overtakes the front particles [37]. This suggests that densification in the lower part of the bed is probably negligible so the granular temperature is increasing then decreasing as the mound passed by and the local angle of repose is changed accordingly. Furthermore, the signals from the point B always end earlier than that from the point A, indicating that at the end of the avalanche some particles stop on the way to the bottom of the surface due to the friction of the wall.

Fig. 7 shows the comparison of the distributions of the avalanche statistics for the point A and B when the drum is rotating at a speed of 1.53 RPM. Fig. 7(a) shows that the rest time,  $t_r$ , for these two points are both normally distributed with standard deviations less than 10% of the average (see Table 2), however, the average for point A is smaller. This result also agrees with the visual observation and the synchronized SVS measurement that the avalanche duration for point A is longer. Furthermore, using the average of resting time of 0.59 s ( $t_r = 0.54$  s and  $t_r = 0.64$  s for points A and B respectively) with the rotational speed of 1.53 RPM in Eq. (2) gives an average  $\Delta\theta = 5.35^\circ \pm 0.45^\circ$ , which is almost identical to the value obtained from image analysis,  $\Delta\theta = 5.4^\circ \pm 1.2^\circ$ , taking into account the experimental errors.

Fig. 7 (b) and (c) shows that the duration time,  $t_d$ , and the peak of the particle fluctuation speed of the avalanches,  $\delta v_p^2$ , for the points A and B are also both normally distributed but negatively correlated as point B has lower avalanche duration and higher particle fluctuations, as shown in Fig.7 (d). This is identical to glass particle experiments where plots of each avalanching mentioned characteristics revealed that a higher particle fluctuation velocity tends to lead to shorter avalanches (*i.e.* higher dissipation leads to faster ‘cooling’) [22]. Fischer *et al.* [31] also observed that avalanches that start at a higher angle tend to stop at a lower angle in a shorter time.

Fig. 7 (Color online) The comparison of the distributions of different avalanching characteristics obtained for point A (black) and B (gray) in the drum at a rotating speed of 1.53 RPM: (a) the rest time,  $t_r$ , (b) the avalanche duration time,  $t_d$ , (c) the peak of the particle fluctuation speed of the avalanches,  $\delta v_p^2$ . The solid curves represent the best fit of a Gaussian distribution to the experimental data, with the averages and standard deviations indicated in Table 2. (d) The peak of the particle fluctuation velocity,  $\delta v_p^2$ , vs. corresponding duration time,  $t_d$ , for each of the avalanches observed at point A (black dot) and B (grey cross, red online) in the drum. The black solid and grey (red online) dash lines represent the best linear fit to the data respectively.

Fig. 8 (a) shows the normally distributed lag time,  $t_l$ , of the start of the avalanches between the point A and B with the average value of 0.061 s, which agrees with the value of 0.07 s obtained by the cross-correlation method as shown in figure 8(b), but bigger than that we measured in the bottom part of the drum [31].

Fig. 8(a) The lag time,  $t_l$ . The data was accumulated from 344 separate avalanches events over 500 s. The solid curves represent the best fit of a Gaussian distribution to the experimental data, with the averages and standard deviations indicated in Table 2. (b) The normalized cross correlation function,  $f(\tau)_{cc}$ , of the particle fluctuation velocity,  $\delta v^2$ , between the point A and B at 1.53RPM.

Table 2 The averages and standard deviations of the Gaussian distributions of the  $t_d$ ,  $t_r$  and  $\delta v_p^2$ .

### C. Variation of slumping statistics with drum speed

Fig. 9(a) shows the comparison of the average rest times,  $t_r$ , and the average avalanche duration time,  $t_d$ , for the point A with drum rotational speed and the related Froude number ( $Fr$ ), which is defined as  $Fr = \omega^2 D / 2g$ . As can be seen from this figure, the average duration time is almost constant under the slumping regime, while the average rest time decreases with increasing drum rotational speed according to the following expression (coefficient of determination of the fitting,  $R^2=0.99$ )

$$t_r = 0.11/\omega - 0.2 \quad (7)$$

Furthermore, using  $t_r$  in Eq. (2) indicates that  $\Delta\theta$  is not constant but, rather, decreases linearly with rotational speed as shown in Fig. 9(b). This result is similar to that of the spherical glass beads [22]. The transition to rolling regime occurs approximately at a rotational speed of 3 RPM and corresponding  $Fr = 4.8 \cdot 10^{-4}$  (not shown here) which is an order of magnitude higher than for smooth glass particles (order of  $10^{-5}$ ), in line with previous studies.

For comparison, Fig. 9(b) also shows the upper,  $\theta_U$ , lower angle of repose,  $\theta_L$ , and the corresponding  $\Delta\theta$  by the imaging technique. It indicates that both  $\theta_U$  and  $\theta_L$  increase slightly with increasing of the drum speed, which is in line with the previous experimental study [37]. While the variation of  $\Delta\theta$  by the imaging technique is not as obvious as that obtained from SVS measurement, mostly due to amplitude of experimental error.

Fig. 9 (a) The comparison of the average rest time,  $t_r$ , (open circles) and the average avalanche duration time,  $t_d$ , (triangle) vs. drum speed and Froude number. Lines are the best reciprocal law fit for  $t_r$  (solid line) and linear fit to the  $t_d$  (dash line) for the point A. The variation of (b)  $\theta_U$  (triangle), and  $\theta_L$  (open circle) (c)  $\Delta\theta$  by SVS (open circle) and imaging technique (triangle), with the rotating speeds. The solid and the dash line represent the linear fitting to the data respectively. (d) The comparison of the average of the peak of particle fluctuation speed,  $\langle \delta v_p^2 \rangle$ , of the avalanches for the point A (top) and B (bottom) vs. the rotating speeds and Froude number. The solid and dash line represents the best line fitting to the data for the point A and B respectively.

Fig. 9(c) shows that the comparison of the averages of the peak of particle fluctuation speed of avalanche,  $\langle \delta v_p^2 \rangle$ , from all the avalanches in 500 s with the rotating speeds for the points A and B. This shows that the instantaneous particle fluctuation speed of the granular flow during avalanche increases linearly with the drum speed which is in line with our previous study [22]. This is also in line with the more general observation that the granular temperature scales with forcing velocities in various granular systems [46], although these systems were time-independent whilst it is time-dependent case here.

### D. Comparison of avalanching statistics in the middle of drum with that near the wall

Fig. 10 shows an example of the synchronized particle fluctuation velocity,  $\delta v^2$ , over five slumping cycles at a drum speed of 1.53 RPM from the middle top, point C, and middle bottom point, D, of the inclined surface. Compared with those from the point A and B, the particle fluctuation speed of the avalanches are lower for the point C and D as clearly seen from comparison of average in Table 3 to Table 2. This is in line with the previous reports that the flow velocity of the grains is lower in the middle than that near the front wall of the drum for the wall effect [47, 48]. Furthermore, the difference at the end of the avalanche for the point C and D is almost zero for most of the time which is different from that for the point A and B (shown in Fig. 6) probable due to an absence of wall friction. Again there is a plateau for upper point C in the profile showing the influence of compaction on granular dynamics. Similarl to the lower point near the wall, there are some peaks in the signal for point D indicating that there are some influences due toflowing mound in the middle of the drum as well.



Fig. 10 (Color online) Synchronized particle fluctuation velocity,  $\delta v^2$ , of points C and D over five slumping cycles for a drum rotating at a speed of 1.53 RPM.

Fig. 11 shows the comparison of the distributions of the avalanche statistics for the points C and D when the drum is rotating at a speed of 1.53 RPM. It is clear that the rest time,  $t_r$ , the duration time,  $t_d$ , the peak of the particle fluctuation speed of the avalanches,  $\delta v_p^2$ , and the lag time,  $t_l$ , are normally distributed with different average values for the points C and D. The similar difference of the average avalanching statistics between the point C and the point D can be also measured, as can those near the front of the wall, but with relatively smaller value. Furthermore, an average  $\Delta\theta = 5.1^\circ \pm 0.56^\circ$  can be calculated using the average  $t_r = 0.56$  s from the point C with the rotational speed of 1.53 RPM in Eq. (2), which is also lower than that measured from the point A. This is in agreement with the MR measurement that the  $\Delta\theta$  in the middle of the drum is a little lower than that near the end wall [35]. The lag time,  $t_l$ , between point C and D is a little shorter than that between point A and B, which indicates that the avalanche develops faster in the middle of the drum than near the end wall due to the wall friction.

Fig. 11 The comparison of the distributions for points A (black) and B (gray) in the drum when rotating at a speed of 1.53 RPM for the following parameters: (a) the rest time,  $t_r$ , (b) the avalanche duration time,  $t_d$ , and (c) the peak of the particle fluctuation speed of the avalanches,  $\delta v_p^2$ , (d) the lag time,  $t_l$ . The data was accumulated from 343 separate avalanches events over 500 s. The solid curves represent the best fit of a Gaussian distribution to the experimental data, with the averages and standard deviations indicated in Table 3.

Table 3 The averages and standard deviations of the Gaussian distributions of the  $t_d$ ,  $t_r$  and  $\delta v_p^2$ .

## IV. CONCLUSION

Simple imaging and synchronized double-SVS technique were used to study avalanching of irregular granular material down the surface of a granular bed in a rotating drum. The imaging technique clearly identified the granular compaction at the beginning of the avalanching process as the major difference with spherical particle experiments. Consequently, a formation of the small mound at the centre of the avalanching surface was visually observed midway through the avalanching process whilst the mound moves to the bottom of the free surface at the end of the avalanche event. The imaging technique found the upper and lower angles of repose which are higher than for similar sized spherical glass particles. The determined difference between upper and lower repose angle is in good agreement with SVS measurements. The repose angles difference is decreasing with the rotating speed which can be seen clearly from the SVS result due to its higher sensitivity, but it is less obvious from the imaging results due to experimental errors. The granular temperature increases sharply then plateaus before decreasing sharply during the avalanche event, in contrast to spherical particle avalanching behavior where these transitions are more gradual. The avalanching near the side walls of the drum is slightly different due to observed mound formation so there are usually additional smaller peaks in granular temperature signal during avalanching due to the change in local repose angle. This clearly indicates that the observed plastic deformation is influencing the dynamics of the system in several ways. Further studies involving synchronously the dynamics in the bulk of the drum and surface flow measurement using different particles of various shapes and surface roughnesses are needed to elucidate interplay between granular flow dynamics and plastic deformation relevant to various industrial and natural processes.

**Acknowledgement** —This work has been supported by the National Natural Science Foundation of China (11572201, 91634202), the Innovation Program of Shanghai Municipal Education Commission (15ZZ072). We thank Prof David Reay, Newcastle University, for language editing and proofreading.

## Nomenclature

$A$	projected area of a particle
$AR$	aspect ratio of maximum and minimum diameter of a particle
$C_x$	convexity of a particle

$d$	particle diameter
$d_{p,50}^{sieve}$	median particle diameter by sieving
$d^{EQPC}$	equivalent projected area diameter
$d^{Fmax}$	maximum Feret diameter of a particle
$d^{Fmean}$	mean Feret diameter of a particle
$d^{Fmin}$	the minimum Feret diameter of a particle
$D$	inner diameter of the drum
$Fr$	the Froude number defined as $Fr = \omega^2 D / 2g$
$g$	gravitational acceleration
$I$	light intensity
$L$	length of the drum
$P$	perimeter of a particle
$s_d$	profile area of the drum
$s_g$	profile area of the granular materials
$S^{QP}$	sphericity of a particle
$t_c$	compaction time at the beginning of the avalanche
$t_d$	duration time of an avalanche
$t_l$	lag time between the triggers of the avalanches between the point A and B
$t_r$	rest time between two successive avalanches
$f(s)$	ratio of $s_g/s_d$
$V_2(T)$	variance of light intensity
$\Gamma$	decay rate of auto correlation
$\langle \delta v^2 \rangle$	mean particle velocity fluctuation
$\delta v_p^2$	peak of the particle velocity fluctuation
$\Delta\theta$	difference between upper and lower angle of repose
$\theta_L$	lower angle of repose
$\theta_U$	upper angle of repose
$\lambda$	wavelength of laser light
$\rho$	flow mass density
$\omega$	rotational speed of the drum

## References:

- [1] G.D.R. MiDi, On dense granular flows, Eur. Phys. J. E 14 (2004) 341-365.
- [2] G. Seiden, P.J. Thomas, Complexity, segregation, and pattern formation in rotating-drum flows, Rev. Mod. Phys. 83 (2011) 1323.
- [3] J. Mu, D.D. Perlmutter, The mixing of Granular solids in a rotary cylinder, AIChE J. 26 (1980) 928-934.
- [4] H. Henein, J.K. Brimacombe, A.P. Watkinson, An experimental study of segregation in rotary kilns, Metall. Trans. B 16 (1985) 763-774.
- [5] B.L. Pollard, H. Henein, Kinetics of radial segregation of different sized irregular particles in rotary cylinders, Can. Metall. Quart. 28 (1989) 29-40.
- [6] G.R. Woodle, J.M. Munro, Particle motion and mixing in a rotary kiln, Powder Technol. 76 (1993) 241-245.
- [7] D.R. Van Puyvelde, B.R. Young, M.A. Wilson, S.J. Schmidt, Experimental determination of transverse mixing kinetics in a rolling drum by image analysis, Powder Technol. 106 (1999) 183-191.
- [8] P. Pandey, R. Turton, Movement of different-shaped particles in a pan-coating device using novel video-imaging techniques, AAPS PharmSciTech 6 (2005) E237-E244.
- [9] O. Dubé, E. Alizadeh, J. Chaouki, F. Bertrand, Dynamics of non-spherical particles in a rotating drum, Chem. Eng. Sci. 101 (2013) 486-502.
- [10] H. Kruggel-Emden, S. Rickelt, S. Wirtz, V. Scherer, A study on the validity of the multi-sphere Discrete Element Method, Powder Technol. 188 (2008) 153-165.
- [11] P.W. Cleary, DEM prediction of industrial and geophysical particle flows, Particuology 8 (2010) 106-118.
- [12] G. Lu, J.R. Third, C.R. Müller, Discrete element models for non-spherical particle systems: From theoretical developments to applications, Chem. Eng. Sci. 127 (2015) 425-465.

- [13] W. Zhong, A. Yu, X. Liu, Z. Tong, H. Zhang, DEM/CFD-DEM Modelling of Non-spherical Particulate Systems: Theoretical Developments and Applications, *Powder Technol.* 302 (2016) 108-152.
- [14] K.W. Carley-Macaulay, M.B. Donald, The mixing of solids in tumbling mixers—II, *Chem. Eng. Sci.* 19 (1964) 191-199.
- [15] R. Rutgers, Longitudinal mixing of granular material flowing through a rotating cylinder: Part II. Experimental, *Chem. Eng. Sci.* 20 (1965) 1089-1100.
- [16] H. Henein, J.K. Brimacombe, A.P. Watkinson, Experimental study of transverse bed motion in rotary kilns, *Metall. Trans. B* 14 (1983) 191-205.
- [17] A.A. Boateng, P.V. Barr, Granular flow behaviour in the transverse plane of a partially filled rotating cylinder, *J. Fluid Mech.* 330 (1997) 233-249.
- [18] S. Longo, A. Lamberti, Grain shear flow in a rotating drum, *Exp. Fluids* 32 313-325.
- [19] R. Mueller, P. Kleinebudde, Prediction of tablet velocity in pan coaters for scale-up, *Powder Technol.* 173 (2007) 51-58.
- [20] K. Yamane, M. Nakagawa, S.A. Altobelli, T. Tanaka, Y. Tsuji, Steady particulate flows in a horizontal rotating cylinder, *Phys. Fluids* 10 (1998) 1419-1427.
- [21] S.C. du Pont, R. Fischer, P. Gondret, B. Perrin, M. Rabaud, Instantaneous velocity profiles during granular avalanches, *Phys. Rev. Lett.* 94 (2005) 048003.
- [22] H. Yang, R. Li, P. Kong, Q.C. Sun, M.J. Biggs, V. Zivkovic, Avalanche dynamics of granular materials under the slumping regime in a rotating drum as revealed by speckle visibility spectroscopy, *Phys. Rev. E* 91 (2015) 042206.
- [23] S.H. Chou, S.S. Hsiau, Dynamic properties of immersed granular matter in different flow regimes in a rotating drum, *Powder Technol.* 226 (2012) 99-106.
- [24] H. Komossa, S. Wirtz, V. Scherer, F. Herz, E. Specht, Transversal bed motion in rotating drums using spherical particles: Comparison of experiments with DEM simulations, *Powder Technol.* 264 (2014) 96-104.
- [25] H.T. Chou, S.H. Chou, S.S. Hsiau, The effects of particle density and interstitial fluid viscosity on the dynamic properties of granular slurries in a rotating drum, *Powder Technol.* 252 (2014) 42-50.
- [26] N. Jain, J.M. Ottino, R.M. Lueptow, An experimental study of the flowing granular layer in a rotating tumbler, *Phys. Fluids* 14 (2002) 572-582.
- [27] D.J. Parker, A.E. Dijkstra, T.W. Martin, J.P.K. Seville, Positron emission particle tracking studies of spherical particle motion in rotating drums, *Chem. Eng. Sci.* 52 (1997) 2011-2022.
- [28] S.Y. Lim, J.F. Davidson, R.N. Forster, D.J. Parker, D.M. Scott, J.P.K. Seville, Avalanching of granular material in a horizontal slowly rotating cylinder: PEPT studies, *Powder Technol.* 138 (2003) 25-30.
- [29] C.R. Müller, D.J. Holland, A.J. Sederman, M.D. Mantle, L.F. Gladden, J.F. Davidson, Magnetic Resonance Imaging of fluidized beds, *Powder Technol.* 183 (2008) 53-62.
- [30] R. Bandyopadhyay, A.S. Gittings, S.S. Suh, P.K. Dixon, D.J. Durian, Speckle-visibility spectroscopy: A tool to study time-varying dynamics, *Rev. Sci. Instrum.* 76 (2005) 093110.
- [31] H. Katsuragi, A.R. Abate, D.J. Durian, Jamming and growth of dynamical heterogeneities versus depth for granular heap flow, *Soft Matter* 6 (2010) 3023-3029.
- [32] H. Yang, G.L. Jiang, H.Y. Saw, C. Davies, M.J. Biggs, V. Zivkovic, Granular dynamics of cohesive powders in a rotating drum as revealed by speckle visibility spectroscopy and synchronous measurement of forces due to avalanching, *Chem. Eng. Sci.* 146 (2016) 1-9.
- [33] R. Li, H. Yang, G. Zheng, B.F. Zhang, M.L. Fei, Q.C. Sun, Double speckle-visibility spectroscopy for the dynamics of a passive layer in a rotating drum, *Powder Technol.* 295 (2016) 167-174.
- [34] F. Altuhafi, C. O'sullivan, I. Cavarretta, Analysis of an image-based method to quantify the size and shape of sand particles, *J Geotech. Geoenviron.* 139 (2012) 1290-1307.
- [35] P.A. Lemieux, D.J. Durian, Investigating non-Gaussian scattering processes by using nth-order intensity correlation functions, *JOSA A* 16 (1999) 1651-1664.
- [36] P.-A. Lemieux, D.J. Durian, Quasi-elastic light scattering for intermittent dynamics, *Appl. Opt.* 40 (2001) 3984-3994.
- [37] C.M. Dury, G.H. Ristow, J.L. Moss, M. Nakagawa, Boundary effects on the angle of repose in rotating cylinders, *Phys. Rev. E* 57 (1998) 4491.
- [38] S.R. Mead, P.W. Cleary, G.K. Robinson, Characterising the failure and repose angles of irregularly shaped three-dimensional particles using DEM, *Proceedings of the Ninth International Conference on CFD in the Minerals and Process Industries*, CSIRO, Melbourne, Australia (2012) 10-12.

- [39] A.W. Alexander, B. Chaudhuri, A. Faqih, F.J. Muzzio, C. Davies, M.S. Tomassone, Avalanching flow of cohesive powders, *Powder Technol.* 164 (2006) 13-21.
- [40] G. Lumay, F. Boschini, K. Traina, S. Bontempi, J.C. Remy, R. Cloots, N. Vandewalle, Measuring the flowing properties of powders and grains, *Powder Technol.* 224 (2012) 19-27.
- [41] Y. Gu, S. Chialvo, S. Sundaresan, Rheology of cohesive granular materials across multiple dense-flow regimes, *Phys. Rev. E* 90 (2014) 032206.
- [42] G. Yablokova, M. Speirs, J. Van Humbeeck, J.P. Kruth, J. Schrooten, R. Cloots, F. Boschini, G. Lumay, J. Luyten, Rheological behavior of  $\beta$ -Ti and NiTi powders produced by atomization for SLM production of open porous orthopedic implants, *Powder Technol.* 283 (2015) 199-209.
- [43] N. Vandewalle, G. Lumay, O. Gerasimov, F. Ludewig, The influence of grain shape, friction and cohesion on granular compaction dynamics, *Eur. Phys. J. E* 22 (2007) 241-248.
- [44] F. Zimmer, J.E. Kollmer, T. Pöschel, Polydirectional Stability of Granular Matter, *Phys. Rev. Lett.* 111 (2013) 168003.
- [45] Z. Wang, J. Zhang, Fluctuations of particle motion in granular avalanches - from the microscopic to the macroscopic scales, *Soft Matter* 11 (2015) 5408-5416.
- [46] V. Zivkovic, M.J. Biggs, D.H. Glass, L. Xie, Particle dynamics and granular temperatures in dense fluidized beds as revealed by diffusing wave spectroscopy, *Adv. Powder Technol.* 20 (2009) 227-233.
- [47] N.A. Pohlman, J.M. Ottino, R.M. Lueptow, End-wall effects in granular tumblers: From quasi-two-dimensional flow to three-dimensional flow, *Phys. Rev. E* 74 (2006) 031305.
- [48] M. Arntz, W.K. Den Otter, H.H. Beftink, R.M. Boom, W.J. Briels, The influence of end walls on the segregation pattern in a horizontal rotating drum, *Gran. Matter* 15 (2013) 25-38.